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REVIEW

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A scoping review: the impact of nutritional status on the efficacy, effectiveness, and immunogenicity of COVID-19 vaccines

Vicka Oktaria[1], Bayu Satria Wiratama[1*], Slamet Riyanto[2,4], Ratih Puspitaningtyas Purbaningrum[2,5], Citra Widya Kusuma[1], Lintang Dian Saraswati[6,7], Vitri Widyaningsih[8], Ratih Puspita Febrinasari[8], Ari Probandari[8] and Riris Andono Ahmad[1,3]

Abstract

Background Vaccination is one of the most effective strategies in mitigating the severity of SARS-CoV-2 infection. While a connection between poor nutritional status and diminished immune responses to vaccination has been noted, comprehensive reviews elucidating this association have been scarce. To address this gap, we conducted a scoping review to characterise the relationship between nutritional status (specifically, body mass index (BMI) or micronutrient deficiencies) and the responses to COVID-19 vaccination, encompassing efficacy, effectiveness, and immunogenicity.

Method We searched PubMed, OVID-Medline, Scopus, Cochrane Covid Register, LitCovid, and WHO COVID-19 research databases for studies that reported the association between nutritional status and responses to the COVID-19 vaccines (published between December 20, 2019, and December 30, 2023). Two reviewers independently screened the articles, and disagreements were resolved through consensus or by a third reviewer.

Results Seventy-three out of 1,853 identified articles were included in this review, predominantly featuring cohort designs (72%). Among these studies, 63% reported BMI, 30% focused on micronutrients (specifically vitamin D, selenium, iron, zinc), and 6% examined both. Most studies (84%) focused on vaccine immunogenicity. The most frequently studied vaccines were BNT162b2 (Pfizer, 74%), ChAdOx (AstraZeneca, 23%), and mRNA-1273 (Moderna, 14%). High BMI significantly reduced COVID-19 vaccine immunogenicity in 23 studies, while adequate vitamin D was associated with increased vaccine response in seven studies.

Conclusion Overnutrition and micronutrient deficiencies (vitamin D, iron, selenium and zinc) have been observed to attenuate the potency of COVID-19 vaccines. Future strategies aimed at prioritizing vaccination in obese and overweight individuals, or enhancing their vaccine response, may involve identifying measures such as the provision of booster doses. Additionally, efforts should ensure micronutrient adequacy, including improving vitamin D status through strategies like increased sun exposure or supplementation, particularly for deficient individuals.

Keywords BMI, Obesity, Vitamin D, COVID-19, Vaccines, Immune response

*Correspondence:
Bayu Satria Wiratama
bayu.satria@ugm.ac.id
Full list of author information is available at the end of the article

Introduction

The COVID-19 pandemic has led to health, social, and economic crises on a global scale [1]. As of August 16, 2022, The World Health Organization (WHO) reports that over 590 million people worldwide have been confirmed to have contracted COVID-19, with 6 million reported to have died [2]. This pandemic has further exacerbated health inequalities both within and between countries [3]. Within vulnerable populations, safe and efficacious vaccines play a pivotal role in preventing disease and mitigating the risk of transmission [4].

COVID-19 vaccination is a crucial and effective strategy in the overall pandemic control, particularly in preventing hospitalisation, admission to intensive care units, and fatalities associated with Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) infections [5]. However, the response to the COVID-19 vaccine varies between individuals, affecting both protective efficacy and vaccine's duration of immunity. Vaccine response in individuals is determined by strain virulence, vaccine types and host factors such as age, comorbidities and nutritional status. Poor nutritional status has been associated with reduced antibody production and compromised the ability to generate immune memory cells [6–10].

Reports indicate an escalation in COVID-19 severity among individuals with high body mass index (BMI) or micronutrient deficiencies [11]. Further investigation is warranted to ascertain how nutritional status influences the immune response conferred by COVID-19 vaccination. While some studies have explored the relationship between individual nutritional status and the effect of COVID-19 vaccines, there remains a scarcity of comprehensive literature mapping and reviewing the available evidence on COVID-19 vaccines and poor nutritional status. In response to this gap, we conducted a scoping review to map and describe the association between nutritional status (BMI, as a proxy for macronutrient status, or deficiency in micronutrients) and COVID-19 vaccine responses (including vaccine efficacy, effectiveness, and Immunogenicity).

Methods

We adhered to the standard reporting guidelines outlined by the Preferred Reporting Items for Systematic Review and Meta-Analysis extension for scoping review (PRISMA-ScR) [12]. A detailed account of each step in the scoping review process is provided in the subsequent subsections.

Operational definition, inclusion and exclusion criteria

Vaccine response was defined as any report on either vaccine effectiveness, efficacy, and Immunogenicity. Vaccine effectiveness was defined as vaccine performance in real-world settings to protect individuals from health outcomes like infections, symptomatic diseases, hospitalisation, and deaths. Vaccine efficacy was defined as the performance of a vaccine measured under controlled clinical trial conditions. Vaccine immunogenicity was defined as the production of antibodies directed against viral proteins, including IgG and secretory IgA antibodies, and their functional capacity to neutralise the virus in vitro or to mediate antibody-dependent cellular cytotoxicity.

The inclusion and exclusion criteria for the study were as follows:

Inclusion criteria: (i) original studies, including observational and experimental studies, that reported BMI and micronutrient status related to COVID-19 vaccine effectiveness, efficacy, and Immunogenicity, (ii) studies published between December 20, 2019, and December 30, 2023, written in the English language. Exclusion criteria: (i) Full-text unavailability, and (ii) Studies from grey literature sources.

Searching strategy and selection criteria

We conducted a thorough search across six electronic databases, namely PubMed, OVID-Medline, Scopus, Cochrane Covid Register, LitCovid, and WHO COVID-19 research database, to identify relevant studies published between December 20, 2019, and December 30, 2023. The search strategy and selected keywords are outlined in Supplementary 1. This encompassed a comprehensive set of terms, including ((nutritional status OR malnutrition OR body mass index OR obesity) OR (micronutrient deficiency OR vitamin deficiency)) AND (COVID-19 vaccine) AND (efficacy OR effectiveness OR immunogenicity). Variants and combinations of these search terms were employed and tailored to each specific database. The detailed study protocol has been registered on the Open Science Framework (OSF) [13].

Publication selection

All studies identified from the databases were uploaded to the reference management software, Rayyan—a web-based systematic review tool, facilitating the screening process. Duplicate studies were systematically excluded through the software. Two researchers (SR and RPP) independently screened

titles and abstracts against the predefined inclusion and exclusion criteria. In the case of disagreement between reviewers, resolution was achieved through consensus or consultation of a third reviewer (VO). Full-text articles were retrieved for all studies meeting the eligibility criteria. Studies lacking full-text access were excluded from further consideration.

Data charting management

Data extraction was performed based on the final list of studies. We extracted data from included studies encompassing vaccine responses, study designs, study years, population, types of nutritional status, types of vaccine, study location, age of participants, and year of studies. All data were extracted to a Microsoft Excel database, which the study team had pretested before initiating the extraction process. Themes were identified from the extracted data through careful reading and discussion among the authors. Two authors executed data coding independently, with subsequent discussions to finalize and group codes into overarching themes. Narrative descriptions of the evidence were written for each theme identified during the stages. All authors reviewed these descriptions for clarity and relevance. To enhance readability, specific themes were combined. Given the nature of a scoping review, a risk-bias assessment was not conducted.

Role of funding sources

The funders played no role in the study design, data collection or analysis, decision for publication, and manuscript preparation.

Results

Characteristics of included studies

Figure 1 shows the PRISMA flowchart of this study. Out of 1853 articles found, we removed 432 duplicates in this study. In addition, from the title and abstract screening, we removed 1313 articles that did not meet the eligibility criteria. Finally, after the full-text screening, an additional 35 articles were excluded.

Seventy-three studies were included in our final analysis. The predominant study designs included cohort studies (72%), followed by cross-sectional (14%), case–control (7%), and randomized controlled trials (RCTs) (7%) designs (Table 1).

Most of the studies in each region were conducted in Italy (n= 12/36, 33%, European countries), Turkiye (n= 7/30, 23%, Asia Pacific countries), USA (n= 6/7, 86%, American region). Among these studies, forty-six focused solely on reporting BMI (63%), while twenty-two

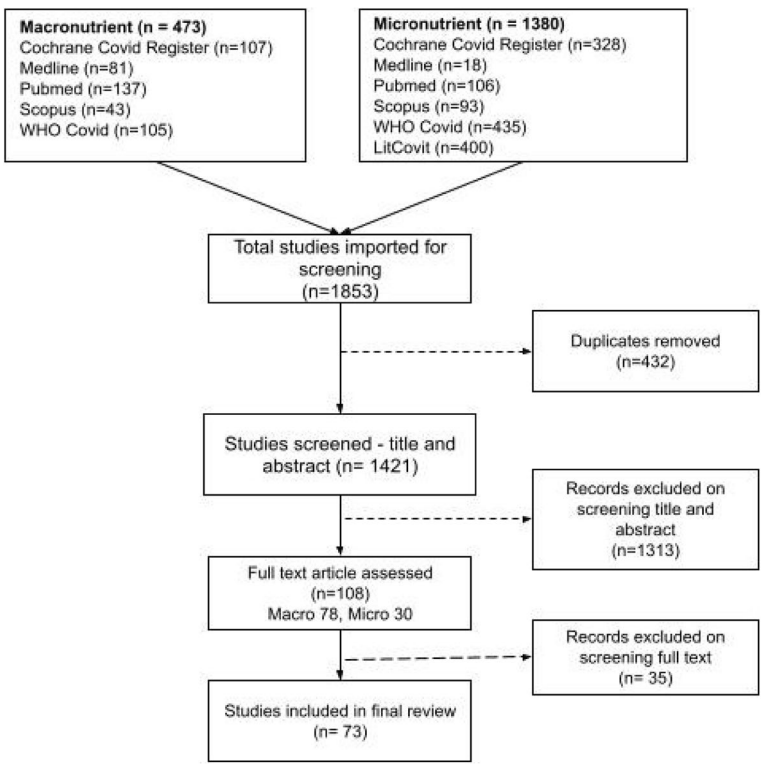

Fig. 1 PRISMA flowchart

Table 1 Characteristics of the included studies

Indicators	*N* = 73	%
Year of publication		
2021	12	16
2022	47	64
2023	14	19
Study design		
RCT	5	7
Cohort	53	72
Case–control	5	7
Cross-sectional	10	14
Region/Country		
Asia Pacific	30	41
Europe	36	49
America	7	10
Population		
Healthy Population	60	82
Individuals with chronic diseases	5	7
Immunocompromised individuals	5	7
Other population[a]	3	4
Type of vaccine*		
Pfizer (BNT162b2)	54	74
AstraZeneca (ChAdOx1-S)	17	23
Moderna (mRNA-1273)	10	14
Sinovac (CoronaVac)	14	19
Covaxin (BBV152)	1	1
Sputnik V (Gam-COVID-Vac)	1	1
Sinopharm (BBIBP-CorV)	2	3
Johnson & Johnson (Ad26.COV2.S)	2	3
No. of vaccine doses		
1 st	7	10
2nd	55	75
3rd	10	14
Not stated	1	1
Nutritional status indicator*		
BMI/Obesity	46	63
Micronutrient		
Vitamin D	12	16
Ferritin (Fe)/Iron	3	4
Selenium	2	3
Zinc	1	1
Multivitamin	2	3
Multimineral	2	3
BMI and Micronutrient	4	6
Malnutrition risk	1	1
Type of outcome		
Vaccine efficacy	1	1
Vaccine effectiveness	10	14
Antibody response/Immunogenicity	61	84
Combination	1	1

* Each percentage except for the type of vaccine

[a] Other population: ED (emergency department) adult patients

studies concentrated on micronutrient deficiencies (vitamin D, selenium, zinc, and iron/ferritin, 29%). The identified types of vaccines were predominantly Pfizer (74%), AstraZeneca (23%), and CoronaVac (19%). A significant proportion of studies reported vaccine immunogenicity or antibody responses (84%), with the second dose of the vaccine being the most frequently reported (75%) [14–18, 20–24].

BMI and vaccine responses

Details of each study are listed in Table 2. Thirty studies out of 46 studies on macronutrients reported a significant association between BMI and any vaccine responses in malnourished individuals, either with over or under-nutrition (24 studies focused only on obesity, 2 studies included obese, overweight, and underweight participants, and 4 studies treated BMI as a continuous variable) and 16 studies found no significant associations [10, 14–42]. A diminished vaccine response was observed in obese only individuals across 24 studies [10, 14–38], while two out of 30 studies highlighted a similar trend in both overweight and underweight individuals [33, 34]. Three studies that reported BMI as a continuous variable demonstrated a trend of increased vaccine response with higher BMI [39, 41, 42]. Twenty-three studies reported significant association between BMI and vaccine response, focusing on immunogenicity [14–30, 33–35, 38, 40–42]. Excluding individuals with acute COVID-19 during the study, obesity was still associated with reduced anti-S IgG levels (OR: 3.87; 95% CI: 1.44–11.99) [15]. The association between obesity and immune response was reported to vary by SARS-CoV-2 variants. Obesity was found to significantly reduce antibody levels against the receptor-binding domain from Wuhan Hu-1 and B.1.1.7 (Alpha), but not B.1.351 (Beta), P.1 (Gamma), or B.1.617.2 (Delta) [26].

Vaccine effectiveness (VE) or efficacy was reported by eight studies with outcomes including VE against COVID-19 infections, emergency department presentations, hospitalisation, ICU admission, and mortality [10, 22, 31, 32, 34, 36, 37, 39]. Breakthrough infection with severe COVID-19 manifestations was reported higher in obese compared to healthy-weight individuals (OR 1.61; 95% CI 1.17—2.21) [36]. Van der Klaauw et al. reported that individuals with severe obesity (BMI >40 kg/m^2) who were vaccinated had a 76% higher likelihood of hospitalisation or death due to COVID-19, with an adjusted rate ratio of 1.76 (95% CI 1.60–1.94) [37]. A study by Piernas et al. reported comparable vaccine effectiveness among overweight or obese individuals with healthy-weight individuals [34].

Table 2 Nutritional status and vaccine responses

No	Author (year)	Year/design/location	Population	Type of vaccine (no of dose)	Exposure description	Exposure (Nutrition Status)	Outcome	Conclusion
Macronutrient								
1	Faizo et al., [14]	2021/Case–control/Saudi Arabia	Case: Obesity class I, II, III, and super obesity $n = 73$ Control: normal BMI $n = 46$	Pfizer-BioNTech, AstraZeneca, Moderna (second dose)	BMI (%); Obesity vs normal	BMI (%) Obesity: 61.3 Normal weight: 38.7	Antibody response/immunogenicity *anti-SARS-CoV-2 Spike (S) neutralizing antibodies*	obesity and vaccine response (Sig, decreased)[a]
2	Glowinska et al., [15]	2021–2022/Cohort/Poland	Adult patients on maintenance hemodialysis ($n = 181$) and peritoneal dialysis ($n = 10$)	Pfizer-BioNTec and Moderna (third dose)	BMI (%); Baseline vs 6 months	BMI (%) Baseline: 26.2 After six months: 28.8 After A booster: 29.7	Antibody response/immunogenicity *anti-SARS-CoV-2 Spike (S)*	obesity and vaccine response (Sig, decreased)
3	Güzel et al., (2021) [16]	2021/Cohort/Turkey	Volunteers Group I ($n = 134$) Group II ($n = 28$) Group III ($n = 21$)	CoronaVac (second dose)	BMI score among three groups of participants	BMI (%) Group 1: 26.9 ± 5.6 Group 2: 28.2 ± 7.1 Group IIIt: 24.8 ± 3.7	Antibody response/immunogenicity *IgG antibody*	obesity and vaccine response (Sig, decreased)
4	Kara et al., (2022a, b) [17, 18]	2021/Case–control/USA	Case: severe obesity, $n = 124$ Control: Subjects who visited the vaccination unit, $n = 166$	Pfizer-BioNTech and CoronaVac (second dose)	BMI (%); Obesity vs normal	BMI (%) Severe Obesity: 42.8 Normal weight: 57.2	Antibody response/immunogenicity *SARS-CoV-2 IgG*	obesity and vaccine response (Sig, decreased)
5	Kara et al.,(2022) [18]	2021/Cross-sectional/Turkey	Patients with obesity (BMI) ≥ 30 kg/m^2, $n = 128$) non-obese control group (BMI < 30 kg/m^2, $n = 147$)	CoronaVac (second dose)	BMI (%); Obese vs non-obese	BMI (%) Obese: 46.5 Non-obese: 53.5	Antibody response/immunogenicity *SARS-CoV-2 IgG*	obesity and vaccine response (Sig, decreased)
6	Kara et al., (2023) [19]	2021/Cross-sectional/Turkey	Case: Elderly patients with obesity (age ≥ 65 years, BMI ≥ 30 kg/m^2, $n = 123$) Adults with obesity (age 18–64 years, BMI ≥ 30 kg/m^2, $n = 47$) Control: Non-obese elderly (age ≥ 65 years, BMI 18.5–29.9 kg/m^2, $n = 75$) Non-obese adults (age 18–64 years, BMI 18.5–29.9 kg/m^2, $n = 105$)	CoronaVac (second dose)	BMI (%); Obese vs non obese; among Eldery and Adult	BMI (%) Elderly: Obese (62.1) Non-obese (37.9) Adult: Obese (30.9) Non-obese (69.1)	Antibody response/immunogenicity *SARS-CoV-2 IgG*	obesity and vaccine response (Sig, decreased)
7	Malavazos et al.,(2022) [20]	2021–2022/Cohort/Italy	Health care workers $n = 1060$	Pfizer-BioNTech (second dose)	BMI (%); Obesity, Overweight, Normal weight, Underweight	BMI (%) Obesity: 11.13 Overweight: 29.34 Normal weight: 56.04 Underweight: 3.49	Antibody response/immunogenicity *IgG-TrimericS antibody*	abdominal obesity and vaccine response (Sig, decreased)

Table 2 (continued)

No.	Author (year)	Year/design/location	Population	Type of vaccine (no of dose)	Exposure description	Exposure (Nutrition Status)	Outcome	Conclusion
8	Mendizabal et al., [21]	2021/Cohort/Argentina	Healthy volunteers $n = 27$ Liver transplant recipients (LTRs) $n = 120$	AstraZeneca, Moderna, Sputnik V, Sinopharm (second dose)	BMI (median (IQR)); LTRs vs Controls	BMI (median (IQR)) LTRs: 27.7 (24.4–31.2) Controls: 27.2 (24.1–31.2)	Antibody response/immunogenicity *Anti-SARS-CoV-2 Spike (S)*	obesity and vaccine response (Sig, decreased)
9	Palacka et al., [22]	NI/Cohort/Slovakia	Staff at the National Comprehensive Cancer Center (NCCC) $n = 94$	Pfizer-BioNTech (second dose)	BMI (%); Obesity, Overweight, Normal weight, Underweight	BMI (%) Obesity: 15.96 Overweight: 28.72 Normal weight: 51.06 Underweight: 4.26	Vaccine effectiveness *COVID-19 positivity* *Adverse events* Antibody response/immunogenicity *IgG counts* *T cell activation*	BMI and vaccine response (NS) obesity and vaccine response (Sig, decreased)
10	Palaia et al., [23]	2021/Cohort/Italy	Oncologic patients $n = 44$; Healthy controls $n = 44$	Pfizer-BioNTech (second dose)	BMI (%) only for Case; Obese, Overweight, Normal weight	BMI (%) on Case group: Obese (11.4) Overweight (25.0) Normal weight (63.6)	Antibody response/immunogenicity *anti-SARS-CoV-2 IgG antibodies*	obesity and vaccine response (Sig, decreased)
11	Papadopoulos et al., [24]	2021/RCT/Greece	Healthy study participants $n = 302$	Pfizer-BioNTech (second dose)	BMI (Median (range)) kg/m^2	BMI (Median (range)) kg/m^2 24.8 (27)	Antibody response/immunogenicity *Neutralizing antibodies (NAbs)*	obesity and vaccine response (Sig, decreased)
12	Pellini et al., (2021) [25]	NI/Cohort/Italy	Healthcare workers (HCW) $n = 252$	Pfizer-BioNTech (first dose)	BMI (%) Obesity, Overweight, Normal weight, Underweight	BMI (%) Obesity (10.3) Overweight (23.4) Normal weight (58.7) Underweight (7.5)	Antibody response/immunogenicity *IgG antibodies*	obesity and vaccine response (Sig, decreased)
13	Tang et al., (2022) [26]	2020–2021/Cohort/USA	Healthcare workers $n = 399$	Pfizer-BioNTech (second dose)	BMI (%) SARS-CoV-2 Infection Only, SARS-CoV-2 Vaccination Only, Vaccination After SARS-CoV-2 Infection: very obese, obese, overweight, normal weight, underweight	BMI (%) SARS-CoV-2 Infection Only; Very Obese (9.2) Obese (29.2) Overweight (25) Normal weight (28.3) Underweight (0.8) SARS-CoV-2 Vaccination Only; Very Obese (3.4) Obese (21.1) Overweight(30.4) Normal weight (40.9) Underweight (2.1) Vaccination After SARS-CoV-2 Infection; Very Obese (4.8) Obese (33.3) Overweight: (28.6) Normal weight (31) Underweight(2.4)	Antibody response/immunogenicity *immunoglobulin G (IgG) levels; Receptor-binding domain (RBD)*	obesity and vaccine response (Sig, decreased)

Table 2 (continued)

No	Author (year)	Year/design/location	Population	Type of vaccine (no of dose)	Exposure description	Exposure (Nutrition Status)	Outcome	Conclusion
14	Watanabe et al., [27]	2021/Cohort/Italy	Healthcare workers *n* = 86	Pfizer-BioNTech (second dose)	BMI (%) Obesity, Overweight, Normal weight	BMI (%) Obesity (9.5) Overweight: (27.4) Normal weight (63.1)	Antibody response/immunogenicity *SARS-CoV-2 antibody titres*	obesity and vaccine response (Sig, decreased)
15	Watanabe et al., [28]	2021/Cohort/Italy	Patients with obesity *n* = 21	Pfizer-BioNTech (second dose)	Median BMI (kg/m2) Pre-intervention vs post-intervention	Median BMI (25 th,75 th percentile) Pre-intervention 40.95 (39.30, 42.76); post-intervention 36.83 (34.93, 38.23)	Antibody response/immunogenicity *anti-SARS CoV-2 S IFN secretion*	obesity and vaccine response (Sig, decreased)
16	Yamamoto et al., [29]	2021/Cross-sectional/Japan	Health care workers *n* = 2,435	Pfizer-BioNTech (second dose)	BMI (%) Obesity I, Obesity II, Overweight, Normal weight, Underweight	BMI (%) Obesity I (11.7) Obesity II (2.7) Overweight (13.9) Normal weight (60.0) Underweight (11.8)	Antibody response/immunogenicity *anti-SARS-CoV-2 Spike (S)*	obesity and vaccine response (Men: Sig, decreased) (Woman: NS)
17	Zhu et al., (2022) [30]	2021/Cross-sectional/China	Obesity and overweight *n* = 132 Normal BMI *n* = 82	CoronaVac (second dose)	BMI (%) Obesity and overweight vs Normal	BMI (%) Obesity and overweight: 61.7 Normal: 38.3%	Antibody response/immunogenicity *anti-RBD-IgG; NAbs*	obesity and vaccine response (Sig, decreased)
18	Alharbi et al., [31]	2020–2021/Cohort/Saudi Arabia	Subjects received one dose *n* = 18,543	Pfizer-BioNTech, AstraZeneca (first dose)	BMI (%), obesity among infected vs not infected	BMI (%), obesity among infected individuals (5.2) Obesity among not infected individuals (3.5)	Vaccine effectiveness *Infection post-vaccination*	obesity and vaccine response (Sig, decreased)
19	Saciuk et al., [32]	2021/Cohort/Israel	All active HMO members *n* = 1,650,885	Pfizer-BioNTech (second dose)	BMI (%) Obesity among Only vaccinated group, Became vaccinated, and Only unvaccinated	BMI (%) Obesity among Only vaccinated group (23.6), Became vaccinated (14.1), Only unvaccinated (15.1)	Vaccine Effectiveness *Covid-19 infection, hospitalisation and mortality rates*	obesity and vaccine effectiveness (Sig, decreased)
20	Albanesi et al., [33]	2021/Cross-sectional/Italy	Healthy participants *n* = 299	AstraZeneca, Moderna (second dose)	BMI (%) Obesity vs Non-obese	BMI (%) Overweight/obese (25) Normal weight/underweight (75)	Antibody response/immunogenicity *anti-SARS-CoV-2 IgG*	obesity and vaccine response (Sig, decreased) Underweight-overweight and vaccine response (Sig, increased)

Table 2 (continued)

No	Author (year)	Year/design/location	Population	Type of vaccine (no of dose)	Exposure description	Exposure (Nutrition Status)	Outcome	Conclusion
21	Piernas et al., [34]	2020–2021/Cohort/UK	The anonymized research database of patients from over 1700 general practices $n = 9,171,524$ adults	Pfizer-BioNTech AstraZeneca Moderna (third dose)	BMI (%) Obesity, overweight, normal weight, underweight (First dose, Second dose, Third dose)	BMI (%) Obesity First dose (2.8) Second dose (53.7) Third dose (29.4) Overweight First dose (2.7) Second dose (51.9) Third dose (28.6) Normal weight First dose (3.5) Second dose (52.8) Third dose (20.5) Underweight First dose (6.30) Second dose (51.1) Third dose (10.0)	Vaccine effectiveness *hospital admission and death*	obesity-underweight and vaccine effectiveness (Sig, decreased)
22	Zhang et al., (2022)	2020–2021/Cohort/China	Healthcare workers $n = 1156$	Vero Cell (second dose)	BMI (%) Obesity and overweight vs Normal weight or less	BMI (%) Obesity and overweight (30.8) Normal weight or less (69.2)	Antibody response/immunogenicity *SARS-CoV-2 S-RBD domain antibody*	obesity and vaccine response (Sig, decreased)
23	Fan et al. [36]	2021/Cross-sectional/UK	Based on the UK Biobank database and the 2021 National Health Interview Survey (NHIS) who tested positive for SARS-COV-2: Participants aged > 50 years, $n = 20.362$ Participants aged > 18 years, $n = 2.588$	Pfizer-BioNTech, AstraZeneca (first dose)	BMI Obesity (%) among Vaccinated vs Non-vaccinated	BMI Obesity (%) Vaccinated (27.9) Non-vaccinated (30.7)	Vaccine effectiveness *COVID-19-related hospital admission and death*	obesity and vaccine effectiveness (Sig, decreased)
24	Mallah et al., [10]	2020–2021/Case–control/Spain	Secondary data: 909,636 individuals based on The Galician Healthcare Service (SERGAS) data with 1,606,749 SARS-CoV-2 test results	Pfizer-BioNTech AstraZeneca (third dose)	BMI (%) obesity among SARS-COV-2 Infection group, hospitalisation group, ICU admission group, In-hospital Death group	BMI (%) Obesity among: SARS-COV-2 Infection (13.5) Hospitalisation (31.5) ICU admissions (41.5) In-hospital Death (28.5)	Vaccine effectiveness *Hospitalisation, ICU admissions, in-hospital death*	obesity and vaccine effectiveness (Sig, decreased)

Table 2 (continued)

No	Author (year)	Year/design/location	Population	Type of vaccine (no of dose)	Exposure description	Exposure (Nutrition Status)	Outcome	Conclusion
25	van der Klaauw et al., [37]	2020–2022/Cohort/UK	Secondary data: from EAVE II data = 1.734.710 individuals aged ≥ 18 years with BMI recorded	Pfizer-BioNTech AstraZeneca (second dose)	BMI (%) Severe obesity, obesity, overweight, normal weight, underweight	BMI (%) Severe obesity (2.8) Obesity (15.8) Overweight (67.7) Normal weight (12.7) Underweight (1.0)	Vaccine effectiveness *hospitalisation and mortality*	obesity and vaccine effectiveness (Sig, decreased)
26	Herzberg et al., [38]	2020/Cohort/Germany	Healthcare workers 184 participants provided blood specimens and a completed questionnaire	Pfizer-BioNTech (second dose)	BMI (%) Obesity and non-obesity	BMI (%) Obesity (16.3) Non-Obesity (83.7)	Antibody response/immunogenicity *Anti-SARS-CoV-2 binding antibodies*	Obesity and vaccine response (Sig, decreased)
27	Mallow et al., [39]	2021/Cohort/USA	ED adult presentations *n* = 13,203	Pfizer-BioNTech Moderna (second dose)	BMI (%) Obese, Overweight, Normal weight or less	BMI (%) Obese: 31.6 Overweight: 32.0 Normal weight or less: 36.4	Vaccine effectiveness *emergency department (ED) presentations due to SARS-COV-2 infection*	increasing BMI and vaccine effectiveness (Sig, increased)[b]
28	Choi et al., [40]	2021/Cohort/Korea	Fully vaccinated HCWs *n* = 79	AstraZeneca (second dose)	BMI (SD) kg/m^2	BMI (SD) kg/m^2 23.7(5)	Antibody response/immunogenicity *T-spot assay*	Increasing BMI and vaccine response (Sig, decreased)
29	Delgado et al., (2022) [41]	2020–2021/Cohort/Spain	Healthcare workers *n* = 2174	Pfizer-BioNTech, Moderna (second dose)	BMI (Median, IQR) (kg/m^2)	BMI (Median, IQR) (kg/m^2) 24.1 (23.9, 24.2)	Antibody response/immunogenicity *anti-S protein antibody*	increasing BMI and vaccine response (Sig, increased)
30	Jolliffe et al., (2022a, b) [42, 73]	2020–2021/Cohort/UK	UK residence aged ≥ 16 years *n* = 9101	AstraZeneca (second dose)	BMI (%) Obese, Overweight, Normal	BMI (%) Obese (18.3) Overweight (32.7) Normal (48.8)	Antibody response/immunogenicity *IgG/A/M serostatus*	increasing BMI and vaccine response (Sig, increased)
31	Herzberg et al., [43]	2020–2021/Cohort/Germany	Hospital employees *n* = 562 out of 871 (64.5% response rate)	Pfizer-BioNTech (second dose) and AstraZeneca (first dose)	BMI (%); Obesity	BMI (%) Pfizer: 17.3 AZ: 23.9	Antibody response/immunogenicity *SARS-CoV-2-IgG ratio*	obesity and vaccine response (NS)
32	Uysal et al., (2022) [44]	2021/Cohort/Turkey	Healthcare workers *n* = 314	CoronaVac (second dose)	BMI (%) Obesity, Overweight, Normal weight	BMI (%) Obesity (12.4) Overweight (39.9) Normal weight (47.6)	Antibody response/immunogenicity *Receptor-binding domain (RBD)*	obesity and vaccine response (NS)
33	Katz et al., (2021) [45]	2021/Cohort/USA	Patients with multiple sclerosis *n* = 48	Pfizer-BioNTech, Moderna, Johnson & Johnson's (first dose)	BMI (Mean (Range)) kg/m^2 OCR treatmenT vs NTZ treatment	BMI (Mean (Range)) kg/m^2 OCR treatment: 27.2 (19.7–42.2) NTZ treatment: 23.2 (19.3–31.1)	Antibody response/immunogenicity *SARS-CoV-2 spike protein antibodies; SARS-CoV-2 T-cell response*	obesity and vaccine response (NS)

Table 2 (continued)

No	Author (year)	Year/design/location	Population	Type of vaccine (no of dose)	Exposure description	Exposure (Nutrition Status)	Outcome	Conclusion
34	Lee et al. (2021) [46]	2021/Cohort/South Korea	Healthcare workers *n* = 447	AstraZeneca (second dose)	BMI (%) Obesity, Overweight, Normal weight, Underweight	BMI (%) Obesity (19.7) Overweight (17.0) Normal weight (56.1) Underweight (7.2)	Antibody response/immunogenicity *anti-SARS-CoV-2 spike (S) protein receptor binding domain (RBD) antibody*	obesity and vaccine response (NS)
35	Mitsunaga et al., [47]	2021/Cohort/Japan	Hospital's workers *n* = 374	Pfizer-BioNTech (second dose)	BMI (%) Obesity, Overweight, Normal weight, Underweight	BMI (%) Obesity (5.0) Overweight (14.2) Normal weight (71.7) Underweight (9.1)	Antibody response/immunogenicity *anti-SARS-CoV-2 antibody titer*	obesity and vaccine response (NS)
36	Ponce et al., (2022) [48]	2021/Cohort/Portugal	Patients with chronic kidney disease (CKD-5D) in dialysis Vaccinated group: 321 patients Control (COVID-19-Recovered): 183 patients	Pfizer-BioNTech (second dose)	BMI (Median (IQR)) kg/m^2 Vaccinated Group vs COVID-19-Recovered	BMI (Median (IQR)) kg/m^2 Vaccinated Group 24.8 (22–28.20) COVID-19-Recovered 24.8 (21.50–29.30)	Antibody response/immunogenicity *anti-Spike IgG level*	obesity and vaccine response (NS)
37	Ali et al. (2021) [49]	2020–2021/Cohort/USA	Participants with multiple sclerosis (MS) and other demyelinating diseases *n* = 53	Pfizer-BioNTech, Moderna (second dose)	BMI (SD) kg/m^2 Healthy controls, Untreated MS, Other DMT Treated MS, Patients on BCDT, Post COVID-19	BMI (SD) kg/m^2 Healthy controls: 23.6 (5.5) Untreated MS: 27.3 (6.2) Other DMT Treated MS: 35.1 (9.9) Patients on BCDT: 32.4 (8.7) Post COVID-19: 33.5 (5.1)	Antibody response/immunogenicity *anti-spike RBD antibodies*	BMI and vaccine response (NS)
38	Balkan et al., (2022) [50]	2021/Cohort/Turkey	Healthcare workers *n* = 175	CoronaVac (second dose)	BMI (%) Obesity, overweight, normal weight	BMI (%) Obesity (14.3) Overweight (34.3) Normal weight (48.6)	Antibody response/immunogenicity *Anti-spike receptor binding domain (RBD) IgG*	BMI and vaccine response (NS)
39	Bates et al., [51]	NI/Cohort/USA	Healthcare workers *n* = 126	Pfizer-BioNTech (second dose)	BMI (%) Obesity, Overweight, Normal weight	BMI (%) Obesity (37.3) Overweight (23.8) Normal weight (38.8)	Antibody response/immunogenicity *receptor binding domain (RBD)-specific IgG and surrogate neutralizing titers*	BMI and vaccine response (NS)
40	Gianserra et al. [52]	2021/Cohort/Italy	People living with HIV (PLWH) *n* = 42	Pfizer-BioNTech (third dose)	BMI (%) Obesity, Overweight, Normal weight	BMI (%) Obesity (19) Overweight (45) Normal weight (36)	Antibody response/immunogenicity *IgG antibodies*	BMI and vaccine response (NS)

Table 2 (continued)

No	Author (year)	Year/design/location	Population	Type of vaccine (no of dose)	Exposure description	Exposure (Nutrition Status)	Outcome	Conclusion
41	Guinault et al., [53]	2021/Cohort/French	Patients undergoing maintenance hemodialysis *n* = 252	Pfizer-BioNTech (second dose)	BMI (SD) kg/m^2	BMI (SD) kg/m^2 26.1 (5.5)	Antibody response/immunogenicity *anti-spike IgG antibodies*	BMI and vaccine response (NS)
42	Held et al., [54]	2021/Cohort/Germany	Healthcare workers *n* = 80	Pfizer-BioNTech (third dose)	BMI (SD) kg/m^2	BMI (Mean (SD)) kg/m^2 25.1 (4.3)	Antibody response/immunogenicity *SARS-CoV-2 IgG antibody*	BMI and vaccine response (NS)
43	Pellini et al., (2021) [55]	2021/Cohort/Italy	Healthcare workers *n* = 248	Pfizer-BioNTech (third dose)	BMI (%) Obesity, Overweight, Normal weight, Underweight	BMI (%) Obesity (10.0) Overweight (22.6) Normal weight (59.7) Underweight (7.7)	Antibody response/immunogenicity *IgG antibodies*	BMI and vaccine response (NS)
44	Priddy et al., (2022) [56]	2021/Cohort/New Zealand	BNT162b2 mRNA vaccine recipients in New Zealand *n* = 285	Pfizer-BioNTech (second dose)	BMI (%) Obesity vs Overweight	BMI (%) Obesity (56.1) Overweight (28.1) Normal weight (15.8)	Antibody response/immunogenicity *anti-S IgG antibody*	BMI and vaccine response (NS)
45	Singh et al. (2021) [57]	2021/Cross-sectional/India	Adult healthcare workers > 18 years of age *n* = 515	Moderna, Covaxin (second dose)	BMI (%) First Dose and second dose: Obesity, Overweight, Normal weight	BMI (%) First Dose Obesity (12.1) Overweight (19.2) Normal weight (68.7) Second Dose Obesity (12.8) Overweight (18.6) Normal weight (68.5)	Antibody response/immunogenicity *IgG antibodies*	BMI and vaccine response (NS)
46	Soegiarto et al., [58]	2021/Cohort/Indonesia	Prospective cohort: Healthcare workers. *n* = 101 Retrospective cohort: hospital staff *n* = 2714	CoronaVac (second dose)	BMI (%) Obesity, overweight, non-obese: Prospective cohort vs retrospective cohort	BMI (%) Prospective cohort: Obesity (11.9) Overweight (29.7) Normal weight (58.5) Retrospective cohort: Obesity (13.2) Overweight (35.4) Normal weight (51.1)	Antibody response/immunogenicity *IgG antibodies*	BMI and vaccine response (NS)
Micronutrient								
47	Santos-Araújo et al., [59]	2021/Cohort/Portugal	Hemodialysis patients *n* = 294	Pfizer-BioNTech (second dose)	Ferritin (Fe)	Ferritin (Fe)	Antibody response/immunogenicity *IgG antibodies*	ferritin (> 600 ng/mL) and vaccine response (Sig, increased)

Table 2 (continued)

No	Author (year)	Year/design/location	Population	Type of vaccine (no of dose)	Exposure description	Exposure (Nutrition Status)	Outcome	Conclusion
48	Faizo et al. [60]	2021/Case–control/Saudi Arabia	College students and staff Case: Iron deficient individuals *N* = 63 Control: healthy individuals *N* = 67	Pfizer-BioNTech, Moderna AstraZeneca (second dose)	Hemogloblin (g/dl) and Ferritin (ng/mL): Case vs Control	Iron Haemogloblin (g/dl) Case: 12.4 ± 1.4 Control: 15.6 ± 1.7 Ferritin (ng/mL) Case: 13.3 ± 12.2 Control: 66.3 ± 29.1	Antibody response/immunogenicity *IgG antibodies*	Iron and vaccine response (NS)
49	Tene (2023) [61]	2020/Cohort/Israel	MHS database: Israel residents aged > 16 years *n* = 184,171	Pfizer-BioNTech (second dose)	Iron deficiency (%) Severe Iron-deficiency anaemia (IDA) vs Mild IDA Functional Iron Deficiency (ID), Absolute ID, ID	Iron Deficiency Anemia (%) Severe Iron-deficiency anemia (IDA) (70.4) Mild IDA (42.0) Iron Deficiency (%) Functional Iron Deficiency (ID) (33.6) Absolute ID (41.8) ID (28.1)	Vaccine effectiveness *preventing SARS-CoV-2 infection, hospitalisation, and mortality*	Iron Deficiency and vaccine effectiveness (Sig, decreased)
50	Cesur et al. [62]	2022/RCT/Turkey	Female volunteers aged 18–23 years with vitamin D deficiency Experimental group = 14 Control group = 14	Pfizer-BioNTech Sinovac (second dose)	Vitamin D (25(OH) D(ng/mL)) Vit.D supplemented group vs No supplemented group	Vitamin D (25(OH) D(ng/mL)) Vitamin D supplemented group: 11.05 (1.39) No supplemented group: 13.90 (6.28)	Antibody response/immunogenicity *IgG antibodies*	vitamin D and vaccine response (Sig, increased)
51	Fanne et al., (2022) [63]	2022/Cohort/Israel	Naïve subjects insured by the Leumit Health Service HMO *n* = 73,254	Pfizer-BioNTech (second dose)	Vit. D 25(OH) Level (%) at baseline among subjects who developed breakthrough infections vs no breakthrough infections	Vitamin D level (%) Breakthrough infection 0–20 ng/ml (46.5) 20–30 ng/ml (35) > 30 ng/ml (18.5) No breakthrough infection 0–20 ng/ml (41) 20–30 ng/ml (38) > 30 ng/ml (21)	Antibody response/immunogenicity *SARS-CoV-2 antibody titer* COVID-19 breakthrough infection	Vitamin D and vaccine response (Sig, increased) Low Vitamin D and vaccine effectiveness (Sig. decreased)
52	Fateh et al., (2023) [64]	NI/RCT/Iraq	Participant who were tested positive for COVID-19 and their serum 25-hydroxy vitamin D (25[OH]D) below 30 ng/mL Intervention group = 246 Placebo group = 179	Pfizer-BioNTech (second dose)	Vitamin D (25[OH] D) serum below 30 ng/mL	Vitamin D (25[OH] D) serum below 30 ng/mL	Antibody response/immunogenicity *IgG antibodies*	vitamin D and vaccine response (Sig, increased)

Table 2 (continued)

No	Author (year)	Year/design/location	Population	Type of vaccine (no of dose)	Exposure description	Exposure (Nutrition Status)	Outcome	Conclusion
53	Filippo et al. [65]	2021/Cohort/Italy	Healthcare workers *n* = 119	Pfizer-BioNTech (second dose)	Vitamin D (25(OH)D) vitamin D deficiency (%)	Vitamin D (25(OH)D) vitamin D deficiency (%): 24.8	Antibody response/immunogenicity *At T0: pan-Immunoglobulins (pan-Ig: IgA, IgG and IgM), At T1, T2, T3 and T4: anti-RBD-S IgTot*	vitamin D deficiency and vaccine response (Sig, decreased)
54	Ma et al. [66]	2021–2022/Cohort/China	Solid cancer patients (SCP-N) and healthy controls (HCs) *n* = 376	CoronaVac (third dose)	Vitamin D serum 25- hydroxyvitamin D (25(OH)D	Vitamin D serum 25- hydroxyvitamin D (25(OH)D	Antibody response/immunogenicity *serum COVID-19 antibody titers*	vitamin D and vaccine response (Sig, increased)
55	Rachman et al. [67]	2021–2022/Cross-sectional/Indonesia	Solid and hematologic cancer patients *n* = 119	Pfizer-BioNTech CoronaVac (second dose)	Vitamin D (25(OH)D (ng/mL) Median; IQR	Vitamin D (25(OH)D (ng/mL) Median (IQR) 36.4 (30.3)	Antibody response/immunogenicity *spike's protein receptor binding Domain (S-RBD) IgG*	vitamin D and vaccine response (Sig, increased)
56	Zelini et al., (2022) [68]	2020–2021/Cohort/Italy	Healthcare workers naïve *n* = 101	Pfizer-BioNTech (second dose)	Vitamin D (25OHD (ng/mL)) Median; IQR before vaccination, Three weeks after the second dose, Six months after the second dose	Vitamin D (25OHD (ng/mL)) Median (Q1-Q3) before vaccination: 16.2 (11.5–22.9) Three weeks after the second dose: 14.6 (10.3–19.5) Six months after the second dose: 26.3 (19.7–32.8)	Antibody response/immunogenicity *anti-S IgG levels and the neutralizing antibody titre*	vitamin D and vaccine response (Sig, increased)
57	Chillon et al., [69]	2021/Cohort/Germany	Healthcare workers *n* = 126	Pfizer-BioNTech (second dose)	Vitamin D 25-Hydroxyvitamin D 25(OH) D (ng/mL) Median (IQR) first vaccination, second vaccination, 3 weeks after the second, 21 weeks after second: female vs male	Vitamin D 25-Hydroxyvitamin D 25(OH) D (ng/mL) Median (IQR) Sampling 1 (first vaccination, *n* = 126) Female: 24 (18.3), Male: 20 (12.3) Sampling 2 (second vaccination, *n* = 115) Female: 22 (16.3), Male: 22 (18.3) Sampling 3 (3 weeks after the second, *n* = 113) Female: 23 (16.3), Male: 19 (11.3) Sampling 4 (21 weeks after second, *n* = 56) Female: 26 (21.3), Male: 27 (21.3)	Antibody response/immunogenicity *IgG antibodies*	vitamin D and vaccine response (NS)

Table 2 (continued)

No	Author (year)	Year/design/location	Population	Type of vaccine (no of dose)	Exposure description	Exposure (Nutrition Status)	Outcome	Conclusion
58	Lavell et al., [70]	2021/Cohort/Netherlands	Healthcare workers *n* = 98	Pfizer-BioNTech (second dose)	Vitamin D (25(OH) D concentrations) nmol/L Median (IQR)	Vitamin D (25(OH) D concentrations) nmol/L Median (Q1-Q3) 55.9 (40.5–69.8)	Antibody response/immunogenicity *binding or neutralizing antibody titers*	vitamin D and vaccine response (NS)
59	Meyers et al. [71]	2021/Cohort/Belgium	Nursing home residents (NHR), *n* = 115 and nursing home staff (NHS), *n* = 254	Pfizer-BioNTech (second dose)	Vitamin D (25(OH) D) Severe Vit.D deficiency (%) and Vit.D deficiency (%): NHRs vs NHS	Vitamin D (25(OH)D) Severe Vit.D deficiency (%) NHRs (24) NHS (11) Vit.D deficiency (%) NHRs (45) NHS (60)	Antibody response/immunogenicity *S1 receptor-binding domain (S1RBD) IgG antibody*	vitamin D and vaccine response (NS)
60	Pavel-Tanasa et al., [72]	2021/Cross-sectional/Romania	Healthy individuals *n* = 192	Pfizer-BioNTech (second dose)	Vitamin D 25(OH)D concentrations	Vitamin D 25(OH)D concentrations	Antibody response/immunogenicity *IgG antibodies*	vitamin D and vaccine response (NS)
61	Jolliffe et al., (2022a, b) [73]	2021/RCT/UK	CORONAVIT trial participants, *n* = 2808	Pfizer-BioNTech, AstraZeneca (second dose)	Vitamin D 800 IU or 3200 IU vitamin D3	Vitamin D (subject Vitamin D status was not measured) 800 IU or 3200 IU vitamin D3	Vaccine efficacy *elevating 25(OH)D concentrations*	vitamin D and vaccine response (NS)
62	Kofahi et al. [74]	2021/Cohort/Jordan	General population *n* = 124	Pfizer-BioNTech (first dose)	Vitamin D and A Vitamin D 25(OH)D level (ng/mL) (mean ± SD): Deficient, Insufficient, Normal Vitamin A Retinol (ng/mL) (mean ± SD): Deficient 1 vs Normal	Vitamin D and A Vitamin D 25(OH)D level (ng/mL) (mean ± SD) 14.3 ± 7.4 Deficient 108 (85%) Insufficient 15 (12%) Normal 4 (3.1%) Vitamin A Retinol (ng/mL) (mean ± SD) 1450 ± 720 Deficient 1 (0.8%) Normal 123 (99.2%)	Antibody response/immunogenicity *IgG antibodies*	vitamin D or vitamin A and vaccine response (NS)
63	Deng et al., [75]	2021–2022/Cohort/China	Healthy adults *n* = 141	CoronaVac (third dose)	Fat-soluble vitamins (Vitamin A, D, and E)	Fat-soluble vitamins (Vitamin A, D, and E)	Antibody response/immunogenicity *anti-SARS-CoV-2 antibodies*	Vitamin D and vaccine response (Sig, increased) Vitamin A & E and vaccine response (NS)
64	Chillon et al., (2022) [76]	2021/Cohort/Germany	healthcare workers *n* = 126	Pfizer-BioNTech (Unidentified)	Zinc	Zinc	Antibody response/immunogenicity *IgG antibodies*	Total serum Zn and vaccine response (NS) Free Zn Concentration and Free Zn/total Zn ratio with vaccine response (Sig, increased)

Table 2 (continued)

No	Author (year)	Year/design/location	Population	Type of vaccine (no of dose)	Exposure description	Exposure (Nutrition Status)	Outcome	Conclusion
65	Demircan et al., [77]	2020–2021/Cohort/Germany	Adult healthcare workers *n* = 126	Pfizer-BioNTech (second dose)	Selenium (moderate Se status)	Selenium (moderate Se status)	Antibody response/immunogenicity *IgG titres*	selenium and vaccine response (NS)
66	Gao et al. [78]	2021/Cohort/China	Healthy adults *N* = 141	CoronaVac (third dose)	Selenium Selenium profile (selenium plasma, selenoprotein)	Selenium Selenium profile (selenium plasma, selenoprotein)	Antibody response/immunogenicity *antibody titers*	selenium and vaccine response (Sig, increased)
67	Rodriguez et al., (2021) [79]	2020–2021/RCT/Spain	Volunteers *n* = 72	Pfizer-BioNTech (second dose)	Zinc (subject zinc status was not measured)	Zinc (subject zinc status was not measured)	Antibody response/immunogenicity *IgG and IgM antibodies*	selenium-zinc and vaccine response (Sig, increased)
68	Chillon et al., [80]	2021/Cohort/Germany	Adult healthcare workers *n* = 126	Pfizer-BioNTech (second dose)	Trace elements copper (µg/L), zinc (µg/L), and selenium (µg/L)	Trace elements copper, zinc, and selenium Copper (µg/L): 1115 Selenium (µg/L): 77 Zinc (µg/L): 800	Antibody response/immunogenicity *IgG antibodies*	decreasing copper & zinc status and vaccine response (Sig, decreased)
Macro- and Micronutrient								
69	Öztürk *et.al.*, (2022) [81]	2022/Case–control/Turkey	Consecutive adults *n* = 124	CoronaVac (second dose)	BMI (%) Overweigtht and Obese Vitamin D (25(OH)D levels) Median (IQR)	BMI (%) Overweigtht + Obese: 50% Vitamin D (25(OH)D levels) Median (IQR) 11.5 (10–17)	Antibody response/immunogenicity *IgG antibodies*	underweight, obesity, and vitamin D and vaccine response (NS)
70	Parthymou et al., (2022) [82]	NI/Cohort/Greece	Health adult *n* = 712	Pfizer-BioNTech (second dose)	Vitamin D (25(OH) D) 25(OH)D quartiles (ng/mL) Q4, Q3, Q2, and Q1	Vitamin D (25(OH) D) 25(OH)D quartiles (ng/mL) Q4: 4.1–18.89 Q3:18.9–25.67 Q2: 25.68–32.99 Q1:33–69.8	Antibody response/immunogenicity *Quantitative determination of antibodies (including IgG)*	BMI (all categories)—vitamin D and vaccine response (NS)
71	Piec et al., [83]	2021/Cohort/UK	Healthcare workers (HCW) *n* = 97	Pfizer-BioNTech (first dose)	BMI (%) Obesity, Overweight, Normal weight	BMI (%) Obesity: 21.4 Overweight: 25.5 Normal weight: 52.1	Antibody response/immunogenicity *anti-spike IgG (quantitative) and anti-nucleocapsid IgG (qualitative)*	BMI and vaccine response (NS) vitamin D and vaccine response (Sig, increased)
72	Visalli et al. [84]	2021/Cohort/Italy	Healthcare workers (HCW) *n* = 200	Pfizer-BioNTech (third dose)	BMI (Mean (SD)) and Vitamin D (ng/mL)	BMI (Mean (SD)) 25.76 (5.3) Vitamin D (ng/mL) (min–max): 23.10 (4.4–60.7)	Antibody response/immunogenicity *IgG antibodies*	BMI and vaccine response (NS) vitamin D and vaccine response (Sig, increased)

Table 2 (continued)

No	Author (year)	Year/design/location	Population	Type of vaccine (no of dose)	Exposure description	Exposure (Nutrition Status)	Outcome	Conclusion
73	Lin et al., (2022) [85]	2021/Cohort/Taiwan	Hemodialysis patients (mean age, 67 ± 13 years) without prior SARS-CoV-2 infection *n* = 206	AstraZeneca (first dose)	Malnourished Risk Nutritional status was assessed by using the Controlling Nutritional Status (CONUT) score: malnourished vs at risk for malnutrition	Malnourished Risk Nutritional status was assessed by using the Controlling Nutritional Status (CONUT) score, an objective indicator of nutrition incorporating serum albumin, total cholesterol, and total lymphocyte count, as well as the subjective global assessment (SGA). 16.5% of patients were classified as malnourished, and 64.1% of patients were at risk for malnutrition based on the CONUT score	Antibody response/immunogenicity *IgG antibodies*	Risk of malnutrition and vaccine response (Sig, increased)

Micronutrients and vaccine responses

Out of seventeen studies [62–69, 73–75, 81, 82, 84], seven [62–64, 66–68, 84] studies reported that higher vitamin D levels significantly enhanced the vaccine response. One study reported a significant difference in mean vitamin D levels between seronegative vs. seropositive groups (20.2 ± 8.7 ng/ml vs. 23.7 ± 6.9 ng/ml ($p < 0.01$) [66].

Nutritional status, comorbidities, and vaccine responses

Two studies involving individuals with comorbidities, specifically cancer [23] and chronic kidney disease with hemodialysis [15], demonstrated that obesity attenuated messenger RNA (mRNA's) vaccine responses (Pfizer–BioNTech or Moderna). As depicted in Table 3, a study by Mendizabal et al. [21] focusing on liver transplant recipients indicated a significant reduction in humoral response with increased BMI (OR, 0.4,95% CI, 0.2–0.7; $p = 0.005$) [21]. Additionally, two studies reported that high ferritin status (> 600 mg/ml) [59] and normal vitamin D status (> 20 ng/ml) [66] increased antibody response among hemodialysis and solid-cancer patients.

Discussion

We have identified 73 studies investigating the association between nutritional status and SARS-CoV-2 vaccine response, including immunogenicity, vaccine efficacy and effectiveness. The evidence consistently indicated that high BMI, particularly in individuals classified as obese, was associated with a reduction in vaccine response. The trend was most pronounced in studies with substantial sample sizes [10, 15–21, 24–26, 29–37, 44] and the reported significant associations persisted across various vaccine types. Malnutrition was frequently associated with decreased detection of serum-neutralizing antibodies against SARS-CoV-2 (anti-SARS-CoV-2 Spike) [15, 21, 60], suggesting an attenuation of immunity [34]. On the contrary, an adequate vitamin D status demonstrated beneficial effects in enhancing immune response following vaccination [62–68, 75, 83, 84].

While the specific biological mechanism underlying obesity's impact on reducing vaccine response remains elusive, existing evidence suggests that obesity is associated with increased COVID-19 severity from both genetic [86] and pathophysiology perspectives [86, 87]. Obesity exhibits a more pronounced clinical impact than other known COVID-19 comorbidities, such as diabetes and cardiovascular diseases [86]. Notably, individuals with obesity face higher odds of hospital admission, intensive care unit (ICU) admission, invasive mechanical ventilation (IMV) use, and mortality [88, 89].

From a pathophysiological standpoint, the heightened expression of angiotensin-converting enzyme two receptors on the cell surface of adipose tissue in individuals with obesity facilitates the invasion of SARS-CoV-2. This may be coupled with reduced diaphragmatic excursion and impaired pulmonary function during infections, resulting in poor ventilation [90]. On the immunological front, adipocytes and macrophages within adipose tissues generate signaling molecules, including TNF, IL-6, leptin, and resistin. These molecules contribute to chronic inflammation, exacerbating metabolic and immunological complications associated with obesity [91, 92]. Obese individuals experienced metabolic imbalances, immune system dysfunction, reduced antibody levels, and decreased pathogen clearance [93]. Prior research on various vaccines has suggested that obesity may compromise T-cell response, potentially explaining the heightened risk for severe COVID-19 outcomes in obese individuals, even post-vaccination [94–96]. Poor seroconversion in people with obesity has been reported [94], raising questions about whether this is due to a failure to boost immunity, or a higher waning rate. This uncertainty underscores the potential necessity for subsequent vaccine boosters in this population.

Likewise, the association between micronutrients and SARS-CoV-2 vaccine responses remains inconclusive, with a broad spectrum of micronutrients under investigation. Prior work has suggested the potential role of micronutrients in gender-specific humoral immunity after SARS-CoV-2 infection [97]. Gao et al. observed that elevated selenium levels enhanced neutralising antibody responses to Omicron in recipients of inactivated COVID-19 vaccines, whereas Nesic et al. reported no association between selenium levels and immunogenicity in mRNA vaccine recipients, indicating potential vaccine-specific effects. [98] Additionally, the combination of selenium and zinc was reported to increase IgG and IgM levels in vaccinated individuals [79]. Among the investigated micronutrients (ferritin, selenium-zinc, and vitamin D), adequate vitamin D consistently emerged as a positive factor in improving vaccine responses [66, 68, 83].

Vitamin D has been reported to have the potential as an immune modulator [99]. The active form of vitamin D, 1.25-dihydroxy vitamin D, modulate the innate and adaptive immune systems in many ways, including enhancing the antimicrobial activities of macrophages and monocytes, and upregulating the expression of the complement receptor immunoglobulin. Supplementation with vitamin D can augment the immune system's ability to respond effectively to the COVID-19 vaccine [100].

Table 3 Effect sizes of the impact of obesity on vaccine responses

Studies*	Population	Outcomes	Adjusted Effect Sizes
Faizo et al., [14]	Obese individuals	Comparison of the proportion of negative serum neutralizing antibodies (anti-SARS-CoV-2 Spike) between obese and healthy weight individuals (serum neutralizing antibodies ≥ 1:20 were considered positive)	OR 0.10 (95% CI: 0.01–0.60)
Piernas et al., [34]	Healthy individuals	Vaccine effectiveness against hospital admission due to COVID-19 14 days after vaccination by BMI status (Vaccinated vs. Unvaccinated individuals)	**Second dose** underweight: OR 0.51 (95% CI: 0.41–0. 63) Healthy weight: OR 0.34 (95% CI:0.32–0.36) Overweight: OR 0.32 (95% CI: 0.30–0.34) Obesity: OR 0.32 (95% CI: 0.30–0.34) **Third dose** underweight: OR 0.05 (95% CI:0.01–0.39) Healthy weight: OR 0.07 (95% CI: 0.05–0.11) Overweight: OR 0.08 (95% CI:0.06–0.10) Obesity: OR 0.05 (95% CI:0.04–0.07)
Glowinska et al., [15]	Adult patients on maintenance hemodialysis and peritoneal dialysis	SARS-CoV-2 anti-spike IgG waning in obese vs. non-obese individuals	OR 3.25 (95% CI: 1.26–9.41)
Mendizabal et al., [21]	Liver transplant recipients (LTRs)	Humoral response in LTRS on the probability of developing anti-spike immunoglobulin G	OR 0.43 (95% CI: 0.23–0.77)
Alharbi et al., [31]	Healthy individuals	Vaccine effectiveness against infection post-vaccination in obese vs. non-obese individuals	OR 1.33 (95% CI: 1.03–1.71)
Zhang et al. (2022) [35]	Healthy individuals (healthcare workers)	SARS-CoV-2 neutralizing antibody presence	OR 0.93 (95% CI: 0.90–0.96)
Fan et al. [36]	Based on the UK Biobank database and the 2021 National Health Interview Survey (NHIS) who tested positive for SARS-COV-2: Participants aged > 50 years	Severe Covid-19 outcome (COVID-19-related hospital admission and death)	Overweight HR 1.02 (95% CI: 0.74–1.41) Obesity HR 1.61 (95% CI: 1.17–2.21)
Jolliffe et al. (2022a, b) [42]	Healthy individuals (UK Residence)	Post-vaccination Sero negativity	BMI 25–30: OR 1.20 (95% CI: 0.95–1.52) BMI > 30: OR 1.30 (95%CI: 0.98–1.72)
Van der Klaauw et al. [37]	Individuals in Scotland were recruited by the EAVE II study	Vaccine effectiveness on hospitalization after two doses. Obesity and severe obesity compared with normal BMI	BMI > 40: RR 1.76 (95% CI: 1.60–1.94) BMI 30–40: RR 1.11 (95% CI: 1.05–1.18)
Mallah et al. [10]	Data from individuals living in Galicia, Spain was collected from Galician Healthcare Service (SERGAS)	Vaccine effectiveness among obese individuals. Complete dose and/or booster dose compared with unvaccinated	COVID-19 infection: Complete dose with VE 67% (95% CI: 65%–69%) Booster dose with VE 91% (95% CI: 83%–96%) COVID-19 hospitalization: Complete and booster dose with VE 78% (95% CI: 73%–83%)
Mallow et al. [39]	Adult individuals presented to the University of Miami Hospital's emergency department (ED)	Vaccine effectiveness among different BMI levels. Fully vaccinated compared with unvaccinated	BMI < 25: VE 66.3% (95% CI: 45.3%–79.2%) BMI 25–29: VE 71.3% (95% CI: 56.1%–81.2%) BMI 30–34: VE 84.5% (95% CI: 71.7%–91.5%) BMI ≥ 35: VE 72.7% (95% CI: 50.5%–84.9%)

* Only studies reported effect sizes as odd ratio/risk ratio or hazard ratio are presented in the table

However, the impact of vitamin D deficiency on vaccine response remains contradictory [101]. A systematic review and meta-analysis of 9 studies (*N*= 2367 participants) reported the association between vitamin D level and the immunogenic response to influenza vaccine. This analysis revealed strain-specific differences in associations with lower serum protection rates of influenza A virus subtype H3 N2 (A/H3 N2) and B strain in vitamin D deficient participants than vitamin D sufficient participants. Overall, no consistent associations were reported between vitamin D and vaccine response to the influenza vaccine [102]. This aligns with our finding that the association between vitamin D status and the COVID-19 vaccine remains unclear. Nevertheless, considering the potential benefits of vitamin D for preventing infection, severe COVID-19 [103, 104], and overall health [99], strategies to improve vitamin D status through sun exposure or supplementation in deficient individuals may be worth considering.

This scoping review provides a comprehensive summary of findings from diverse research endeavours exploring the link between nutritional status and vaccine responses across various types of vaccines and World Bank country classifications. However, several limitations warrant acknowledgement. First, excluding grey literature may have resulted in the omission of valuable data. Moreover, the predominance of observational studies, particularly those employing cohort designs, introduces potential confounding variables that may limit the interpretability of our study. The lack of studies from Africa limits the generalizability of our findings to this region, underscoring the necessity for context-specific investigations. Given the inherent nature of the scoping review, we did not perform a risk of bias assessment in this review. Future studies using a meta-analysis approach are needed to obtain the pooled effect size of BMI and micronutrients associated with vaccine response.

Conclusions

This scoping review maps a wide range of studies examining the relationship between vaccine response, body mass index (BMI), and micronutrient deficiencies. The findings emphasize a diminished vaccine response in individuals with overnutrition or deficiencies in key micronutrients, including vitamin D, iron, selenium, and zinc. It underscores the need for further research into the mechanisms by which obesity affects immunization and the development of targeted immunization strategies to enhance vaccine responses in overweight and obese individuals, particularly given the increasing global prevalence of obesity. An integral aspect of this strategy involves investigating the potential requirement for subsequent vaccine boosters in this particular demographic. Vitamin D supplementation has been routinely used in the management of COVID-19 patients across various settings. Although its role as a vaccine adjuvant has not been well-documented, optimizing vitamin D status—through natural sun exposure or supplementation—may enhance vaccine efficacy, improve overall health, and support the prevention of COVID-19 infections. Further research is needed to clarify its potential benefits in this context.

Authors' contributions
Conceptualization: VO, BSW, CK, RAA. Data curation: SR, RPP, VO, BSW, CK. Formal analysis: SR, RPP, VO, BSW. Supervision: RAA, AP. Writing original draft: VO. Review and editing VO, BSW, CK, RAA, SR, RPP, LDS, VW, AP

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not required.

Consent for publication
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Competing interests
The authors declare no competing interests.

Author details
[1]Department of Biostatistics, Epidemiology, and Population Health, Faculty of Medicine, Public Health and Nursing, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia. [2]Master of Public Health Program, Faculty of Medicine, Public Health and Nursing, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia. [3]Centre for Tropical Medicine, Faculty of Medicine, Public Health and Nursing, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia. [4]Research Center of Public Health and Nutrition, National Research and Innovation Agency (BRIN) Republic of Indonesia, Bogor 16911, Indonesia. [5]Department of Nutrition, Poltekkes Kemenkes Jakarta II, Jakarta 12120, Indonesia. [6]Department of Epidemiology, Faculty of Public Health, Universitas Diponegoro, Semarang 50275, Indonesia. [7]School of Public Health and Social Work, Faculty of Health, Queensland University of Technology, Brisbane 4059, Australia. [8]Faculty of Medicine, Universitas Sebelas Maret, Surakarta 57126, Indonesia.

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References

1. Panneer S, Kantamaneni K, Palaniswamy U, Bhat L, Pushparaj RRB, Nayar KR, et al. Health, Economic and Social Development Challenges of the COVID-19 Pandemic: Strategies for Multiple and Interconnected Issues. Healthcare. 2022;10(5):770.
2. WHO. WHO Coronavirus (COVID-19) Dashboard. WHO Coronavirus (COVID-19) Dashboard. 2022.
3. World Bank Group. Chapter 1. The economic impacts of the COVID-19 crisis. World Bank Group. 2022. Available from: https://www.worldbank.org/en/publication/wdr2022/brief/chapter-1-introduction-the-economic-impacts-of-the-covid-19-crisis. Cited 2022 Dec 3.

4. Lipsitch BM, Dean NE. Viral shedding are important for protection. Science. 2020;370(6518):763–6.
5. Zheng C, Shao W, Chen X, Zhang B, Wang G, Zhang W. Real-world effectiveness of COVID-19 vaccines: a literature review and meta-analysis. Int J Infect Dis. 2022;114:252–60.
6. Vrieling F, Stienstra R. Obesity and dysregulated innate immune responses: impact of micronutrient deficiencies. Trends Immunol. 2023;44(3):217–30. Available from: https://doi.org/10.1016/j.it.2023.01.003.
7. Zimmermann P, Curtis N. Factors that influence the immune response to vaccination. Clin Microbiol Rev. 2019;32(2):1–50.
8. Aranow C. Vitamin D and the immune system. J Investig Med. 2011;59(6):881–6.
9. Gombart AF, Pierre A, Maggini S. A review of micronutrients and the immune system—Working in harmony to reduce the risk of infection. Nutrients. 2021;13(11):1–41.
10. Mallah N, Pardo-Seco J, López-Pérez LR, González-Pérez JM, Rosón B, Otero-Barros MT, et al. Effectiveness of COVID-19 vaccine booster in the general population and in subjects with co-morbidities. A population-based study in Spain. Environ Res. 2022;114252. Available from: https://search.ebscohost.com/login.aspx?direct=true&db=mnh&AN=36096168&site=ehost-live
11. Fedele D, De FA, Riso S, Collo A. Obesity, malnutrition, and trace element deficiency in the coronavirus disease (COVID-19) pandemic: An overview. Nutr J. 2021;81(111016):1–13.
12. Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. Ann Intern Med. 2018;169(7):467–73. https://doi.org/10.7326/M18-0850.
13. Riyanto S, Oktaria V, Wiratama BS, Purbaningrum RP, Kusuma CW, Ahmad RA. A scoping review protocol: the impact of nutritional status on the efficacy, effectiveness, and immunogenicity of COVID-19 vaccines [Internet]. OSF. 2025. Available from: https://osf.io/z8ktv/.
14. Faizo AA, Qashqari FS, El-Kafrawy SA, Barasheed O, Almashjary MN, Alfelali M, et al. A Potential Association between Obesity and Reduced Effectiveness of COVID-19 Vaccine-Induced Neutralizing Humoral Immunity. J Med Virol. 2022. Available from: https://search.ebscohost.com/login.aspx?direct=true&db=mnh&AN=36068377&site=ehost-live
15. Glowinska I, Labij-Reduta B, Juzwiuk J, Lukaszewicz M, Pietruczuk A, Poplawska A, et al. Factors Influencing Longevity of Humoral Response to SARS-CoV-2 Vaccination in Patients with End Stage Kidney Disease Receiving Renal Replacement Therapy. J Clin Med. 2022;11(17). Available from: https://search.ebscohost.com/login.aspx?direct=true&db=mnh&AN=36078913&site=ehost-live
16. Guzel EC Erdal B, Sedef CA. Immunogenicity after CoronaVac vaccination. Rev Assoc Med Bras. 2021;67(10):1403–8 https://pubmed.ncbi.nlm.nih.gov/35018966.
17. Kara Z, Akçin R, Demir AN, Dinç HÖ, Taşkın HE, Kocazeybek B, et al. Antibody Response to SARS-CoV-2 Vaccines in People with Severe Obesity. Obes Surg. 2022a;32(9):2987–93. Available from: https://search.ebscohost.com/login.aspx?direct=true&db=mnh&AN=35802279&site=ehost-live.
18. Kara Z, Akçin R, Demir AN, Dinc HO, Kocazeybek B, Yumuk VD. Risk factors influencing seroconversion after inactive SARS-CoV-2 vaccination in people living with obesity. Obes Facts. 2022;15(5):648–54.
19. Kara Z, Akçin R, Demir AN, Dinc HO, Kocazeybek B, Yumuk VD. Antibody Response to Inactive SARS-CoV-2 Vaccination in a Cohort of Elderly Patients Living with Obesity. Obes Facts. 2023;16(4):374–80. Available from: https://doi.org/10.1159/000530315.
20. Malavazos AE, Basilico S, Iacobellis G, Milani V, Cardani R, Boniardi F, et al. Antibody responses to BNT162b2 mRNA vaccine: Infection-naïve individuals with abdominal obesity warrant attention. Obes (Silver Spring). 2022;30(3):606–13. Available from: https://doi.org/10.1002/oby.23353.
21. Mendizabal M, Ducasa N, Benencio P, Anders M, Cairo F, Barbero M, et al. Heterologous adenovirus-vector/messenger RNA regimen is associated with improved severe acute respiratory syndrome coronavirus 2 humoral response in liver transplant recipients. Hepatol Commun. 2022;6(10):2850–9.
22. Palacka P, Pol'anová M, Svobodová A, Žigmond J, Zanchetta K, Gombárová V, et al. Effectiveness, Adverse Events, and Immune Response Following Double Vaccination with BNT162b2 in Staff at the National Comprehensive Cancer Center (NCCC). Vaccines. 2022;10(4). Available from: https://search.ebscohost.com/login.aspx?direct=true&db=mnh&AN=35455308&site=ehost-live
23. Palaia I, Caruso G, Di Donato V, Vestri A, Napoli A, Perniola G, et al. Pfizer-BioNTech COVID-19 Vaccine in Gynecologic Oncology Patients: A Prospective Cohort Study. Vaccines. 2021;10(1):1–9.
24. Papadopoulos D, Ntanasis-Stathopoulos I, Gavriatopoulou M, Evangelakou Z, Malandrakis P, Manola MS, et al. Predictive Factors for Neutralizing Antibody Levels Nine Months after Full Vaccination with BNT162b2: Results of a Machine Learning Analysis. Biomedicines. 2022;10(2):1–19.
25. Pellini R, Venuti A, Pimpinelli F, Abril E, Blandino G, Campo F, et al. Early Onset of SARS-COV-2 Antibodies after First Dose of BNT162b2: Correlation with Age, Gender and BMI. 2021;9(7). Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8310011
26. Tang L, Cherry S, Tuomanen EI, Kirkpatrick Roubidoux E, Lin CY, Allison KJ, et al. Host Predictors of Broadly Cross-Reactive Antibodies Against Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) Variants of Concern Differ Between Infection and Vaccination. Clin Infect Dis. 2022;75(1):e705–14.
27. Watanabe M, Balena A, Tuccinardi D, Tozzi R, Risi R, Masi D, et al. Central obesity, smoking habit, and hypertension are associated with lower antibody titres in response to COVID-19 mRNA vaccine. Diabetes Metab Res Rev. 2022;38(1): e3465.
28. Watanabe M, Balena A, Masi D, Tozzi R, Risi R, Caputi A, et al. Rapid Weight Loss, Central Obesity Improvement and Blood Glucose Reduction Are Associated with a Stronger Adaptive Immune Response Following COVID-19 mRNA Vaccine. Vaccines. 2022;10(1). Available from: https://search.ebscohost.com/login.aspx?direct=true&db=mnh&AN=35062740&site=ehost-live
29. Yamamoto S, Mizoue T, Tanaka A, Oshiro Y, Inamura N, Konishi M, et al. Sex-associated differences between BMI and SARS-CoV-2 antibody titers following the BNT162b2 vaccine. Obesity (Silver Spring). 2022;30(5):999–1003. Available from: https://search.ebscohost.com/login.aspx?direct=true&db=mnh&AN=35226399&site=ehost-live.
30. Zhu Q, Zhang Y, Kang J, Chen Z, Peng M, Chen M, et al. Weakened humoral and cellular immune response to the inactivated COVID-19 vaccines in Chinese individuals with obesity/overweight. Genes Dis. 2023;10(2):608–17. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2352304222002951.
31. Alharbi NK, Al-Tawfiq JA, Alghnam S, Alwehaibe A, Alasmari A, Alsagaby SA, et al. Outcomes of single dose COVID-19 vaccines: Eight month follow-up of a large cohort in Saudi Arabia. J Infect Public Health. 2022;15(5):573–7. Available from: https://search.ebscohost.com/login.aspx?direct=true&db=mnh&AN=35472755&site=ehost-live.
32. Saciuk Y, Kertes J, Mandel M, Hemo B, Shamir Stein N, Ekka Zohar A. Pfizer-BioNTech vaccine effectiveness against Sars-Cov-2 infection: Findings from a large observational study in Israel. Prev Med (Baltim). 2022;155:106947. Available from: https://search.ebscohost.com/login.aspx?direct=true&db=mnh&AN=34974072&site=ehost-live.
33. Albanesi B, Godono A, Comoretto RI, Casabona E, Curoso G, Leone MV, et al. Immune Response of a Heterologous mRNA-1273 Second-Dose Immunization after a First Dose of ChadOx1 against SARS-CoV-2: A Cross-Sectional Study. Vaccines [Internet]. 2022;10(8):1–9. Available from: https://search.ebscohost.com/login.aspx?direct=true&db=mnh&AN=36016129&site=ehost-live.
34. Piernas C, Patone M, Astbury NM, Gao M, Sheikh A, Khunti K, et al. Associations of BMI with COVID-19 vaccine uptake, vaccine effectiveness, and risk of severe COVID-19 outcomes after vaccination in England: a population-based cohort study. Lancet Diabetes Endocrinol. 2022;10(8):571–80.
35. Zhang H, Liu X, Liu Q, Mei H, Wang Y, Cui G, et al. Serological reactivity of inactivated SARS-CoV-2 vaccine based on an S-RBD neutralizing antibody assay. Int J Infect Dis. 2022;117:169–73.
36. Fan X, Han J, Zhao E, Fang J, Wang D, Cheng Y, et al. The effects of obesity and metabolic abnormalities on severe COVID-19-related outcomes after vaccination: A population-based study. Cell Metab.

2023;35(4):585-600.e5. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1550413123000529.
37. van der Klaauw AA, Horner EC, Pereyra-Gerber P, Agrawal U, Foster WS, Spencer S, et al. Accelerated waning of the humoral response to COVID-19 vaccines in obesity. Nat Med. 2023;29(5):1146–54.
38. Herzberg J, Fischer B, Lindenkamp C, Becher H, Becker AK, Honarpisheh H, et al. Persistence of immune response in health care workers after two doses bnt162b2 in a longitudinal observational study. Front Immunol. 2022;13:839922. Available from: https://search.ebscohost.com/login.aspx?direct=true&db=mnh&AN=35309303&site=ehost-live.
39. Mallow C, Ferreira T, Shukla B, Warde P, Sosa MA, Parekh DJ, et al. Real world SARS-COV-2 vaccine effectiveness in a Miami academic institution. Am J Emerg Med. 2022;54:97–101. Available from: https://search.ebscohost.com/login.aspx?direct=true&db=mnh&AN=35151018&site=ehost-live.
40. Choi H, Lee SM, Lim S, Shin KH, Kim T, Kim WJ, et al. Immunogenicity after Second ChAdOx1 nCoV-19 (AZD1222) Vaccination According to the Individual Reactogenicity, Health Status and Lifestyle. Vaccines. 2021;9(12):1–15.
41. Delgado JF, Berenguer-Llergo A, Julià G, Navarro G, Espasa M, Rodríguez S, et al. Antibody Response Induced by BNT162b2 and mRNA-1273 Vaccines against the SARS-CoV-2 in a Cohort of Healthcare Workers. Viruses. 2022;14(6). Available from: https://pubmed.ncbi.nlm.nih.gov/35746706/
42. Jolliffe DA, Faustini SE, Holt H, Perdek N, Maltby S, Talaei M, et al. Determinants of Antibody Responses to SARS-CoV-2 Vaccines: Population-Based Longitudinal Study (COVIDENCE UK). Vaccines. 2022a;10(10):1601. Available from: https://www.mdpi.com/2076-393X/10/10/1601.
43. Herzberg J, Vollmer T, Fischer B, Becher H, Becker AK, Honarpisheh H, et al. SARS-CoV-2-antibody response in health care workers after vaccination or natural infection in a longitudinal observational study. Vaccine. 2022;40(2):206–12.
44. Uysal E, Gümüş S, Bektöre B, Bozkurt H, Gözalan A. Evaluation of antibody response after COVID-19 vaccination of healthcare workers. J Med Virol. 2022;94(3):1060–6. Available from: https://pubmed.ncbi.nlm.nih.gov/34704620/.
45. Katz J, Lathi E, Douglas E, Jungquist R-M, O'Shea IBA. Humoral and T-cell responses to SARS-CoV-2 vaccination in multiple sclerosis patients treated with ocrelizumab. Mult Scler J. 2021;27(2 SUPPL):786–7. Available from: https://www.embase.com/search/results?subaction=viewrecord&id=L636340092.
46. Lee Moon, Ji-Yong, Lee, Sun-Kyung, Lee, Hyun, Moon, SeolHwa, Chung, Sung Jun, Yeo, Yoomi, Park, Tai Sun, Park, Dong Won, Kim, Tae-Hyung, Sohn, Jang Won, Yoon, Ho Joo, Kim, Sang-Heon SW. Anti-SARS-CoV-2 Spike Protein RBD Antibody Levels After Receiving a Second Dose of ChAdOx1 nCov-19 (AZD1222) Vaccine in Healthcare Workers: Lack of Association With Age, Sex, Obesity, and Adverse Reactions. Front Immunol. 2021;12. Available from: https://search.bvsalud.org/global-literature-on-novel-coronavirus-2019-ncov/resource/en/covidwho-1564401
47. Mitsunaga T, Ohtaki Y, Seki Y, Yoshioka M, Mori H, Suzuka M, et al. The evaluation of factors affecting antibody response after administration of the BNT162b2 vaccine: a prospective study in Japan. PeerJ. 2021;9:e12316. Available from: https://peerj.com/articles/12316.
48. Ponce Peralta, Ricardo, Felix, Carla, Pinto, Carla, Pinto, Bruno, Matos, João Fazendeiro P. Vaccination against SARS-CoV-2 in Haemodialysis Patients: Spike's Ab Response and the Influence of BMI and Age. Int J Environ Res Public Health. 2022;19(16):10091. Available from: https://doi.org/10.3390/ijerph191610091
49. Ali A, Dwyer D, Wu Q, Wang Q, Dowling CA, Fox DA, et al. Characterization of humoral response to COVID mRNA vaccines in multiple sclerosis patients on disease modifying therapies. Vaccine. 2021;39(41):6111–6.
50. Balkan İ, HO D, Can G, Karaali R, Ozbey D, Caglar B, et al. Waning immunity to inactive SARS-CoV-2 vaccine in healthcare workers: booster required. Ir J Med Sci. 2022;1–7. Available from: https://pubmed.ncbi.nlm.nih.gov/35344137/
51. Bates JT, Farmer AP, Bierdeman MA, Ederer DR, Carney LS, Montgomery DD, et al. IgG Antibody Response to the Pfizer BNT162b2 SARS-CoV-2 Vaccine in Healthcare Workers with Healthy Weight, Overweight, and Obesity. Vaccines. 2022;10(4). Available from: https://search.ebscohost.com/login.aspx?direct=true&db=mnh&AN=35455261&site=ehost-live
52. Gianserra L, Donà MG, Giuliani E, Stingone C, Pontone M, Buonomini AR, et al. Immunogenicity and Safety of BNT162b2 Homologous Booster Vaccination in People Living with HIV under Effective cART. Vaccines. 2022;10(8).
53. Guinault D, Bernier M, Delarche A, Neuville S, Milioto O, Molinari N, et al. Immunogenicity of the BNT162b2 Vaccine in Patients Undergoing Maintenance Hemodialysis Is Associated with Medical Conditions. Nephron. 2022:146(6):553–8.
54. Held J, Esse J, Tascilar K, Steininger P, Schober K, Irrgang P, et al. Reactogenicity Correlates Only Weakly with Humoral Immunogenicity after COVID-19 Vaccination with BNT162b2 mRNA (Comirnaty(®)). Vaccines. 2021;9(10):1–12.
55. Pellini R, Venuti A, Pimpinelli F, Abril E, Blandino G, Campo F, et al. Initial observations on age, gender, BMI and hypertension in antibody responses to SARS-CoV-2 BNT162b2 vaccine. EClinicalMedicine. 2021;36:100928.
56. Priddy F, Williams M, Carson S, Lavender B, Mathieson J, Frampton C, et al. Immunogenicity of BNT162b2 COVID-19 vaccine in New Zealand adults. Vaccine. 2022;40(34):5050–9. Available from: https://pubmed.ncbi.nlm.nih.gov/35868948/.
57. Singh A, Phatak S, Singh R, Bhattacharjee K, NK S, Gupta A, et al. Antibody response after first and second-dose of ChAdOx1-nCOV (Covishield(TM)®) and BBV-152 (Covaxin(TM)®) among health care workers in India: The final results of cross-sectional coronavirus vaccine-induced antibody titre (COVAT) study. Vaccine. 2021;39(44):6492–509. Available from: https://pubmed.ncbi.nlm.nih.gov/34600747/.
58. Soegiarto G, Wulandari L, Purnomosari D, Dhia Fahmita K, Ikhwan Gautama H, Tri Hadmoko S, et al. Hypertension is associated with antibody response and breakthrough infection in health care workers following vaccination with inactivated SARS-CoV-2. Vaccine. 2022;40(30):4046–56. Available from: https://search.ebscohost.com/login.aspx?direct=true&db=mnh&AN=35660034&site=ehost-live.
59. Santos-Araújo C, Mota Veiga P, Santos MJ, Santos L, Romãozinho C, Silva M, et al. Time-dependent evolution of IgG antibody levels after first and second dose of mRNA-based SARS-CoV-2 vaccination in haemodialysis patients: a multicentre study. Nephrol Dial Transplant. 2022;37(2):375–81. Available from: https://search.ebscohost.com/login.aspx?direct=true&db=mnh&AN=34634116&site=ehost-live.
60. Faizo AA, Bawazir AA, Almashjary MN, Hassan AM, Qashqari FS, Barefah AS, et al. Lack of Evidence on Association between Iron Deficiency and COVID-19 Vaccine-Induced Neutralizing Humoral Immunity. Vaccines. 2023;11(2):327. Available from: https://www.mdpi.com/2076-393X/11/2/327.
61. Tene L, Karasik A, Chodick G, Pereira DIA, Schou H, Waechter S, et al. Iron deficiency and the effectiveness of the BNT162b2 vaccine for SARS-CoV-2 infection: A retrospective, longitudinal analysis of real-world data. Liu BM, editor. PLoS One. 2023;18(5):e0285606. Available from: https://doi.org/10.1371/journal.pone.0285606
62. Cesur F, Atasever Z, Özoran Y. Impact of vitamin D3 supplementation on COVID-19 vaccine response and immunoglobulin G antibodies in deficient women: A randomized controlled trial. Vaccine. 2023;41(17):2860–7 https://linkinghub.elsevier.com/retrieve/pii/S0264410X23003419.
63. Abu Fanne R, Lidawi G, Maraga E, Moed M, Roguin A, Meisel SR. Correlation between Baseline 25(OH) Vitamin D Levels and Both Humoral Immunity and Breakthrough Infection Post-COVID-19 Vaccination. Vaccines [Internet]. 2022 Dec 10;10(12):2116. Available from: https://www.mdpi.com/2076-393X/10/12/2116
64. Fateh HL, Kareem G, Rezaeian S, Moludi J, Kamari N. The Effect of Vit-D Supplementation on the Side Effect of BioNTech, Pfizer Vaccination and Immunoglobulin G Response Against SARS-CoV-2 in the Individuals Tested Positive for COVID-19: A Randomized Control Trial. Clin Nutr Res [Internet]. 2023;12(4):269. Available from: https://e-cnr.org/x.php?id=https://doi.org/10.7762/cnr.2023.12.4.269
65. di Filippo L, Frara S, Terenzi U, Nannipieri F, Locatelli M, Ciceri F, et al. Lack of vitamin D predicts impaired long-term immune response to COVID-19 vaccination. Endocrine [Internet]. 2023 Aug 17;82(3):536–41. Available from: https://link.springer.com/https://doi.org/10.1007/s12020-023-03481-w

66. Ma Y, Zhu P, Zhong G, Wang D, Cao L, Bai S, et al. Serial negative response after standard and third (Booster) dose of COVID-19 inactivated vaccine is associated with low vitamin D levels in patients with solid cancers. Front Med. 2022;9: 898606.
67. Rachman A, Iriani A, Priantono D, Rumondor BB, Betsy R, Juanputra S. The correlation between serum 25-hydroxy-vitamin D levels and anti-SARS-CoV-2 S-RBD IgG and neutralizing antibody levels among cancer patients receiving COVID-19 vaccines. Front Nutr. 2022;9(1066411):1–12.
68. Zelini P, D'Angelo P, Cereda E, Klersy C, Sabrina P, Albertini R, et al. Association between Vitamin D Serum Levels and Immune Response to the BNT162b2 Vaccine for SARS-CoV-2. Biomedicines. 2022;10(1993):1–9.
69. Chillon TS, Demircan K, Heller RA, Hirschbil-Bremer IM, Diegmann J, Bachmann M, et al. Relationship between Vitamin D Status and Antibody Response to COVID-19 mRNA Vaccination in Healthy Adults. Biomedicines. 2021;9(11):1–18.
70. Lavell AHA, Schramade AE, Sikkens JJ, van der Straten K, van Dort KA, Slim MA, et al. 25-Hydroxyvitamin D concentrations do not affect the humoral or cellular immune response following SARS-CoV-2 mRNA vaccinations. Vaccine. 2023. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0264410X2300957X
71. Meyers E, De Smet E, Vercruysse H, Callens S, Padalko E, Heytens S, et al. No Significant Association between 25-OH Vitamin D Status and SARS-CoV-2 Antibody Response after COVID-19 Vaccination in Nursing Home Residents and Staff. Vaccines. 2023;11(8):1343. Available from: https://www.mdpi.com/2076-393X/11/8/1343.
72. Pavel-Tanasa M, Constantinescu D, Cianga CM, Anisie E, Mereuta AI, Tuchilus CG, et al. Adipokines, and not vitamin D, associate with antibody immune responses following dual BNT162b2 vaccination within individuals younger than 60 years. Front Immunol. 2022;13. Available from: https://www.frontiersin.org/articles/10.3389/fimmu.2022.1000006/full
73. Jolliffe DA, Vivaldi G, Chambers ES, Cai W, Li W, Faustini SE, et al. Vitamin D Supplementation Does Not Influence SARS-CoV-2 Vaccine Efficacy or Immunogenicity: Sub-Studies Nested within the CORONAVIT Randomised Controlled Trial. Nutrients. 2022b;14(18):3821. Available from: https://www.mdpi.com/2072-6643/14/18/3821.
74. Kofahi HM, Badran BR, Nimer RM, Atoom AM, Al Hersh SM. Exploring the Effects of Vitamin D and Vitamin A Levels on the Response to COVID-19 Vaccine. Vaccines. 2023;11(9):1509. Available from: https://www.mdpi.com/2076-393X/11/9/1509.
75. Deng Y, Huang L, Liu P, Geng X, Lin Z, Zheng Z, et al. Association of fat-soluble vitamins (A, D, and E) status with humoral immune response to COVID-19 inactivated vaccination. Front Nutr. 2023;10. Available from: https://www.frontiersin.org/articles/10.3389/fnut.2023.1167920/full
76. Chillon T, Maares M, Demircan K, Hackler J, Sun Q, Heller RA, et al. Serum Free Zinc Is Associated With Vaccination Response to SARS-CoV-2. Front Immunol. 2022;13:906551. Available from: https://pubmed.ncbi.nlm.nih.gov/35844578/.
77. Demircan K, Chillon TS, Sun Q, Heller RA, Klingenberg GJ, Hirschbil-Bremer IM, et al. Humoral immune response to COVID-19 mRNA vaccination in relation to selenium status. Redox Biol. 2022;50: 102242.
78. Gao S, Ren N, Sun T, Nie Q, Liu S, Geng X, et al. Association of selenium profile with neutralizing antibody response to inactivated SARS-CoV-2 vaccination. J Trace Elem Med Biol. 2023;80:127295. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0946672X23001712.
79. Rodriguez J, Bifano M, E RG, CM P, AO T, MS F, et al. Effect and Tolerability of a Nutritional Supplement Based on a Synergistic Combination of β-Glucans and Selenium- and Zinc-Enriched Saccharomyces cerevisiae (ABB C1(®)) in Volunteers Receiving the Influenza or the COVID-19 Vaccine: A Randomized, Double-Bl. Nutrients. 2021;13(12). Available from: https://pubmed.ncbi.nlm.nih.gov/34959898/
80. Chillon TS, Demircan K, Hackler J, Heller RA, Kaghazian P, Moghaddam A, et al. Combined copper and zinc deficiency is associated with reduced SARS-CoV-2 immunization response to BNT162b2 vaccination. Heliyon. 2023;9(10):e20919. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2405844023081276.
81. Öztürk Yılmaz, Niyazi Samet, Ulukanlıgil, Mustafa R. The relationship between serum vitamin D and antibody response following two doses of inactivated COVID-19 vaccine. Turkish J Biochem / Turk Biyokim Derg. 2022;1. Available from: https://doi.org/10.1515/tjb-2022-0123
82. Parthymou A, Habeos EE, Habeos GI, Deligakis A, Livieratos E, Marangos M, et al. Factors associated with anti-SARS-CoV-2 antibody titres 3 months post-vaccination with the second dose of BNT162b2 vaccine: a longitudinal observational cohort study in western Greece. BMJ Open. 2022;12(5):e057084. Available from: https://pubmed.ncbi.nlm.nih.gov/35589363/.
83. Piec I, Cook L, Dervisevic S, Fraser WD, Ruetten S, Berman M, et al. Age and vitamin D affect the magnitude of the antibody response to the first dose of the SARS-CoV-2 BNT162b2 vaccine. Curr Res Transl Med. 2022;70(3): 103344.
84. Visalli G, Laganà A, Lo Giudice D, Calimeri S, Caccamo D, Trainito A, et al. Towards a Future of Personalized Vaccinology: Study on Individual Variables Influencing the Antibody Response to the COVID-19 Vaccine. Vaccines. 2023;11(2):217. Available from: https://www.mdpi.com/2076-393X/11/2/217.
85. Lin T yun, Hung N kuan, Hung S chun. Association of malnutrition with SARS-CoV-2 vaccine response in patients undergoing hemodialysis. Clin Nutr. 2022;41(12):2683–90.
86. Leong A, Cole JB, Brenner LN, Meigs JB, Florez JC, Mercader JM. Cardiometabolic risk factors for COVID-19 susceptibility and severity: A Mendelian randomization analysis. PLoS Med. 2021;18(3):1–17.
87. Yang J, Hu J, Zhu C. Obesity aggravates COVID-19: A systematic review and meta-analysis. J Med Virol. 2021;93(1):257–61.
88. Sawadogo W, Tsegaye M, Gizaw A, Adera T. Overweight and obesity as risk factors for COVID-19-associated hospitalisations and death. BMJ Nutr Prev Heal. 2022;5(1):10–8. Available from: https://nutrition.bmj.com/lookup/doi/10.1136/bmjnph-2021-000375.
89. Huang Y, Lu Y, Huang YM, Wang M, Ling W, Sui Y, et al. Obesity in patients with COVID-19: a systematic review and meta-analysis. Metabolism. 2020;113:154378. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0026049520302420.
90. Sanchis-Gomar F, Lavie CJ, Mehra MR, Henry BM, Lippi G. Obesity and Outcomes in COVID-19: When an Epidemic and Pandemic Collide. Mayo Clin Proc. 2020;95(7):1445–53.
91. Bastard JP, Maachi M, Lagathu C, Kim MJ, Caron M, Vidal H, et al. Recent advances in the relationship between obesity, inflammation, and insulin resistance. Eur Cytokine Netw. 2006;17(1):4–12. Available from: https://www.ncbi.nlm.nih.gov/pubmed/16613757.
92. Xie L, Ortega MT, Mora S, Chapes SK. Interactive Changes between Macrophages and Adipocytes. Clin Vaccine Immunol. 2010;17(4):651–9. https://doi.org/10.1128/CVI.00494-09.
93. Andersen CJ, Murphy KE, Fernandez ML. Impact of Obesity and Metabolic Syndrome on Immunity. Adv Nutr. 2016;7(1):66–75 https://academic.oup.com/advances/article/7/1/66/4524061.
94. Painter SD, Ovsyannikova IG, Poland GA. The weight of obesity on the human immune response to vaccination. Vaccine. 2015;33(36):4422–9.
95. Sheridan PA, Paich HA, Handy J, Karlsson EA, Hudgens MG, Sammon AB, et al. Obesity is associated with impaired immune response to influenza vaccination in humans. Int J Obes. 2012;36(8):1072–7.
96. Paich HA, Sheridan PA, Handy J, Karlsson EA, Schultz- S, Hudgens MG, et al. immune response to pandemic H1N1 influenza A virus. Obes (Silver Spring). 2013;21(11):2377–86.
97. Panahibakhsh M, Amiri F, Doroudi T, Sadeghi M, Kolivand P, Alipour F, et al. The association between micronutrients and the SARS-CoV-2-specific antibodies in convalescent patients. Infection. 2022;50(4):965–72. https://doi.org/10.1007/s15010-022-01774-2.
98. Nešić A, Stojsavljević A, Jagodić J, Čavić M, Stefanović A, Manojlović D, et al. A six-month study of anti-SARS-CoV-2 BNT162b2 mRNA vaccination: A comparative analysis of essential trace elements and anti-RBD IgG sera levels. J Trace Elem Med Biol. 2022;74: 127079.
99. Charoenngam N, Holick MF. Immunologic Effects of Vitamin D on Human Health and Disease. Nutrients. 2020;12(7):2097.
100. Inserra F, Tajer C, Antonietti L, Mariani J, Ferder L, Manucha W. Vitamin D supplementation: An alternative to enhance the effectiveness of vaccines against SARS-CoV-2? Vaccine. 2021;39(35):4930–1. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0264410X21009087.
101. Small AG, Harvey S, Kaur J, Putty T, Quach A, Munawara U, et al. Vitamin D upregulates the macrophage complement receptor immunoglobulin in innate immunity to microbial pathogens. Commun Biol. 2021;4(1):401.
102. Lee MD, Lin CH, Lei WT, Chang HY, Lee HC, Yeung CY, et al. Does Vitamin D Deficiency Affect the Immunogenic Responses to Influenza Vaccination?

A Systematic Review and Meta-Analysis. Nutrients. 2018;10(4):409. Available from: https://www.mdpi.com/2072-6643/10/4/409.
103. Dissanayake HA, de Silva NL, Sumanatilleke M, de Silva SDN, Gamage KKK, Dematapitiya C, Kuruppu DC, Ranasinghe P, Pathmanathan SKP. Prognostic and therapeutic role of vitamin D in COVID-19: systematic review and meta-analysis. J Clin Endocrinol Metab. 2022;107(5):1484–502.
104. Kaya MO, Pamukcu E, Yakar B. The role of vitamin D deficiency on COVID-19: A systematic review and meta-Analysis of observational studies. Epidemiol Health. 2021;43:1–15.

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